THE HIGGS MASS BOUND IN GAUGE EXTENSIONS

OF THE MSSM

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Outline

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- WARM UP-$U(1)_x$: Greater Higgs mass

- AN EXTRA $SU(2)$: Asymptotic freedom

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INTRODUCTION

• The MSSM has been the most promising candidate for beyond SM for the last 20 years because:

- • Gives a solution to the hierarchy problem. Softens the sensitivity to high scales in the Higgs mass.

- • Can naturally accommodate unification.

- • has a natural candidate for dark matter. LSP.

• Although it has a number of problems:

- • Large number of parameters $O(100)$. This is much larger than the 19 of the SM.

- • SUSY breaking and flavour. There is no unique way to break SUSY without any additional problems.

- • μ-problem. The Higgs mass term in the superpotential has to be $\sim$ EW.

● But clearly the MSSM is being experimentally constrained by the Higgs mass
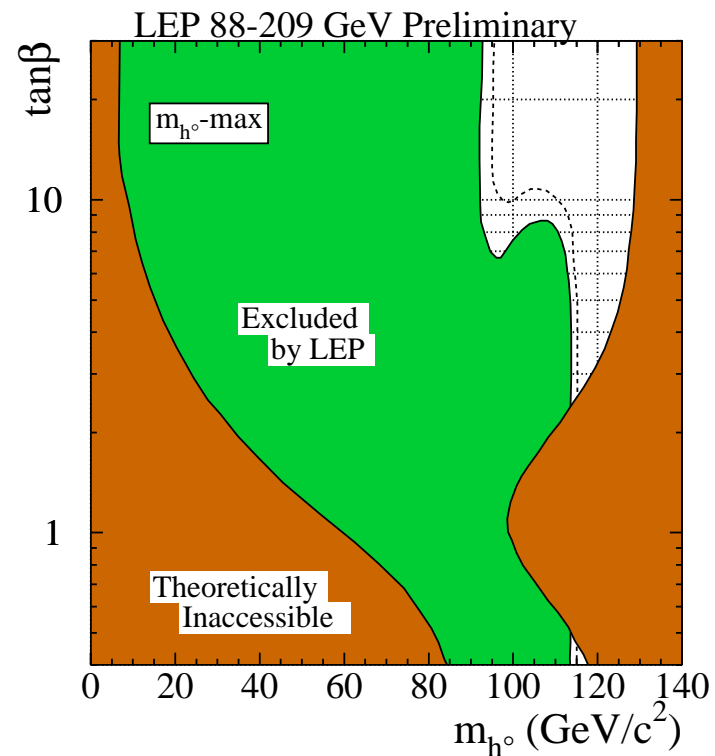
● In order for the MSSM not to be ruled out it has to be fine-tunned,

$M_{SUSY} >$ EW so there must be cancellations at the level of few percent.

• This fine-tunning is caused by the dual role played by the superparners in general and the stops specifically:

- On the one hand stops cancel the quadratic divergence of the Higgs coming from top loops. But SUSY breaking leaves quadratic sensitivity to the stop mass. $\longrightarrow M_{stop} \sim$ EW

- On the other hand the experimental bound can only be satisfied for large values of the stop parameters (~ 1 TeV). $\longleftarrow$ This is because the tree-level mass is fixed by SUSY

$$m_h^2 \quad \leq \quad m_z^2$$

• There are ways to increase the previous tree level values via superpotential couplings, NMSSM or through the D-term. In this talk I am going to talk about the later case.

WARM UP-$U(1)_x$

● The gauge structure of the MSSM is enlarged with an extra $U(1)$:

$$
\begin{aligned}
Q, L &: 0 \\
D^c, E^c, \overline{H} &: +1/2 \\
U^c, H, N^c &: -1/2 \\
\Phi, \Phi^c &: \pm q
\end{aligned}
$$

● With this structure the D-term reads as:

$$
\frac{g_x^2}{2} \left[\frac{1}{2} \left| \overline{H} \right|^2 - \frac{1}{2} \left| H \right|^2 + q \left| \phi \right|^2 - q \left| \phi^c \right|^2 + \dots \right]^2
$$

● We are going to suppose that SUSY breaking occurs at a similar scale of the breaking of the $U(1)$.

● Bellow the scale where $U(1)$ is broken the field ϕ gets a soft mass and it can be integrated out leading to the following non-susy term:

$$\frac{g_x^2}{2} \left(\frac{1}{2} \left| \overline{H} \right|^2 - \frac{1}{2} \left| H \right|^2 \right)^2 \quad \times \quad \left(1 + \frac{M_{Z'}^2}{2m_\phi^2} \right)^{-1}$$

● Which translates into the following tree-level bound for the Higgs mass upon EW breaking:

$$m_{h^0}^2 \quad < \quad \left(\frac{g^2}{2} + \frac{g'^2}{2} + \frac{g_x^2}{2} \left(1 + \frac{M_{Z'}^2}{2m_\phi^2} \right)^{-1} \right) v^2 \cos^2 2\beta$$

● There are certain constrains on the parameters coming from EW observables and perturbativity. So taking the following parameters:

- $\alpha_x \equiv g_x^2/4\pi = 1/35$ at a few TeV. The beta-function coefficient for the gauge coupling g_x is $b_x = 7 + 2q^2$. For the value $q = 1/2$, the coupling runs semi-perturbatively at the GUT scale (*i.e.*, $\alpha_x(\Lambda_{GUT}) \sim 1$).

- A Z' mass of 2.2 TeV, just above the current LEP lower bound.

- $m_\phi = 6.6$ TeV at low energies. One loop corrections to the Higgs mass parameter from the supersymmetry breaking are finite and relatively small (< 250 GeV). The two-loop RGE contribution from m_ϕ^2 is smaller.

● We get that in the decoupling limit (large $\tan\beta$ and m_A)

$$m_h \;\; = \;\; 116 \text{ GeV}$$

that value will be lifted by radiative corrections. So all the parameter space of this model is compatible LEP data.

AN EXTRA $SU(2)$

• The reason why the effect in the previous model is limited is that the new $U(1)$ is infrared free, so the natural value for g_x is very small at low energies. we am going to present a model with asymptotic freedom so the gain is much greater.

• Lets suppose that the gauge structure is now $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ and the matter content is as follows:
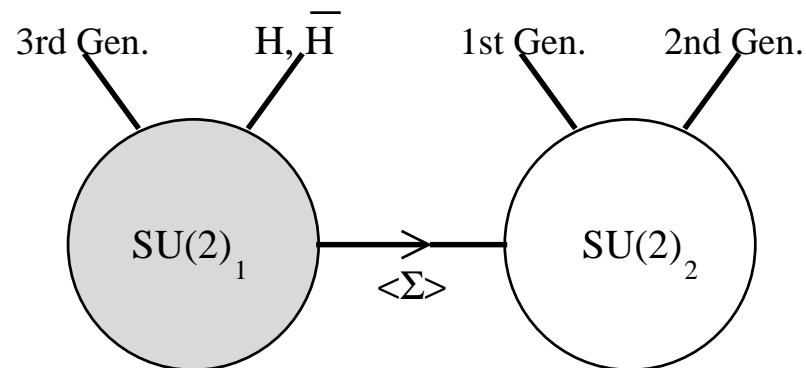
- There is a bidouplet Σ whose vev will break the two $SU(2)$'s to the diagonal $SU(2)_L$.

- $\mathbf{SU(2)_1}$: The third family plus the two higgs doublets $H, \overline{H}$. (This group is asymptotically free!!)

- $\mathbf{SU(2)_2}$: The first two families plus two extra higgs-like supermultiplets $H', \overline{H}'$.

- Yukawa couplings for the first two generations are generated via couplings to $H', \overline{H}'$ and a superpotential couplings of the form $\lambda' \overline{H} \Sigma H'$.

$$
\begin{aligned}
W \;=\;& \mu' H' \bar{H}' + \lambda' H_2 \Sigma H' + \\
& y_u Q_1 u_1 H' + y_d Q_1 d_1 \bar{H}' + ...
\end{aligned}
$$

- If $\mu' \geq <\Sigma>$, we integrate out the spectator Higgses:

$$
y_d \frac{\lambda' <\Sigma>}{\mu'} H_2 Q_1 u_1
$$

● The D-term of the two $SU(2)$'s is:

$$\frac{g_1^2}{8} \left(\text{Tr} \left[\Sigma^\dagger \sigma^a \Sigma \right] + H^\dagger \sigma^a H - \overline{H} \sigma^a \overline{H}^\dagger + \dots \right)^2 + \frac{g_2^2}{8} \left(\text{Tr} \left[\Sigma \sigma^a \Sigma^\dagger \right] \right)^2$$

● On top of which we have the following potential for Σ:

$$V_\Sigma \;=\; \frac{1}{2} B \Sigma \Sigma + h.c. + m^2 |\Sigma|^2 + \frac{\lambda^2}{4} |\Sigma \Sigma|^2$$

● For sufficient large B Σ develops a vev, $\langle \Sigma \rangle = u\mathbf{1}$ and integrating out the massive fields we get the following potential for the Higgs fields:

$$\frac{g^2}{8} \Delta \left(H^\dagger \vec{\sigma} H - \overline{H} \vec{\sigma} \overline{H}^\dagger \right)^2 + \frac{g_Y^2}{8} \left(|\overline{H}|^2 - |H|^2 \right)^2,$$

- In where:

$$\Delta = \frac{1 + \frac{2m^2}{u^2}\frac{1}{g_2^2}}{1 + \frac{2m^2}{u^2}\frac{1}{g_1^2+g_2^2}} \quad \text{and} \quad \frac{1}{g^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2}$$

- Upon EWSB the tree-level Higgs mass satisfies:

$$m_{h^o}^2 \quad < \quad \frac{1}{2}\left(g^2\Delta + g_Y^2\right)v^2\cos^2 2\beta$$

- As before parameters are chosen to satisfy both perturbativity and EW constrains:

  - Oblique corrections to W and Z masses.

  - Vertex corrections to f_L.

  - Non-oblique contributions to G_F.

  - Small triplet VEV in Σ.

  - Non-universal corrections to 3rd family couplings!

● The bound can be parametrized in $c^2 \equiv \cos^2 \theta$ where $\tan \theta = g1/g2$
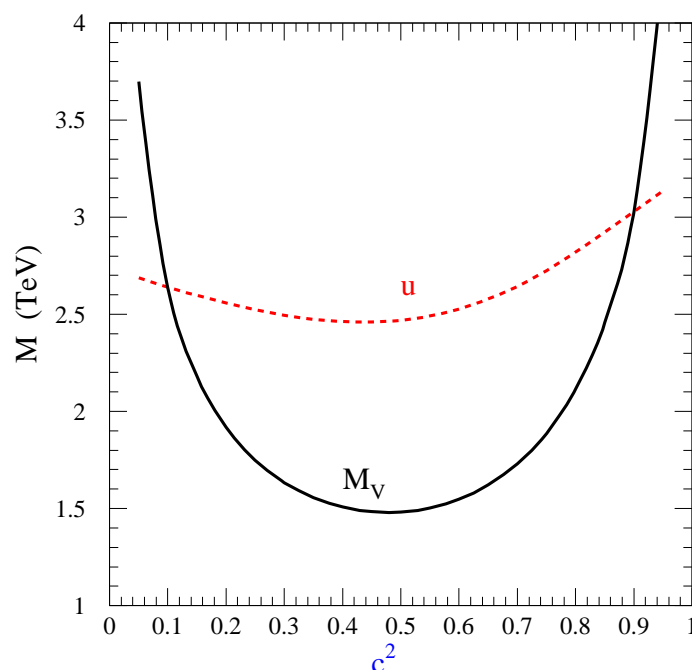
● The bound is minimize when the couplings have same size, although we are really interested when $g1 \gg g2$ which pushes us to a bigger bound on the scales.

- Lets pick up some points in the parameter space:

  - $g_1(u) = 1.80,\ g_2(u) = .70$, with $c^2 = .8$ inspired by a GUT with $g_1(\Lambda_{GUT}) = .97$. Additional spectator fields are included in the running to aid in unification.

  - $u = 2.7$ TeV, above the lower limit from electroweak constraints, giving $M_{W'}, M_{Z'} \sim 2$ TeV.

  - $m = 10\ \mathrm{TeV}$. One-loop finite corrections to the Higgs mass parameter < 300 GeV and two-loop RGE contributions are also under control.

- For the above values we get $\Delta = 6.97$ and $m_h = 214$ GeV for the large $\tan \beta$ and decoupling limit.

- One can push up $g_1(\Lambda_{GUT})$ ($c^2 \sim .95$) paying the price of fine-tunning and one can get $\Delta \sim 20$ and $m_h \sim 350$ GeV.

- Other interesting features of this model are:

  - Since the top-yukawa gets an extra contribution from a big coupling, $\tan \beta < 1$ is consistent without a Landau pole.

  - Unification is achieved to $SU(5) \times SU(5)$. Two extra triplets of $SU(2)_2$ are needed to ensure the proper running.

  - First two families yukawas can be naturally suppressed if the extra $H', \overline{H}'$ acquire masses above the breaking scale.

  - Using the idea of complementarity we could let $SU(2)_1$ confine, the Higgs and third family will appear as composites, and the Higgs mass could get its maximum value.

CONCLUSIONS AND OUTLOOK

- The parameter space of the MSSM is starting to be squeezed because of the *not-yet-found* Higgs. Moreover, any scenario not ruled out is fine-tuned.

- We have constructed simple extensions that allow to raise the tree-level value of the Higgs mass via extra gauge groups or extra superpotential couplings.

- We have proven that there can be SUSY theories with a heavy Higgs contrary to the common lore.

- One of the phenomenological properties of these models is allowing $\tan \beta < 1$. The gauge extensions have a similar Higgs sector as in the MSSM and the minimization of the potential is as well equivalent.

- There are, however, some open questions:

  - Extended study of the phenomenology, specially the $\tan \beta < 1$ region.

  - Possible UV embedding of these models with a complete SUSY breaking sector.

  - Other possibilities such as the additions of triplets or confining groups.

- It is fair to say that there are easy ways to solve the fine-tunning problem of the MSSM regarding the higgs mass. It is not generally true that any SUSY model will predict a light higgs. On the other hand one can construct models where the LEP bound doesn't apply.